The Structure of Dark Matter Halos

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A large number of astronomical and cosmological observations now provide compelling evidence for the existence of dark matter. Although the ultimate nature of the dark matter remains unknown, its large-scale dynamics is completely consistent with that of a self-gravitating collisionless fluid. In an expanding universe, the gravitational instability is the driver of the growth of structure in the dark matter, the final distribution arising from the nonlinear amplification of primordial density fluctuations. The existence of localized, highly overdense clumps of dark matter, termed halos, is an essential feature of nonlinear gravitational collapse in cold dark matter models.

Dark matter halos occupy a central place in the paradigm of structure formation—gas condensation, resultant star formation, and eventual galaxy formation occur within halos. The distribution of halo masses, and the halo mass function and its time evolution are sensitive probes of cosmology, particularly so at low redshifts, $z < 2$, and high masses. This last feature allows cluster observations to constrain the dark energy content and its equation of state. In addition, phenomenological modeling of the dark matter in terms of halos requires knowledge of the halo mass distribution and density profiles, as does the halo occupancy distribution (HOD) approach to modeling galaxy bias.

Because accurate theoretical results for the mass function (and other halo properties) do not exist, many numerical studies of halos and their properties have been carried out. Despite the intuitive simplicity and practical importance of the halo paradigm, halo definitions and characterizations have been somewhat ad hoc, mostly because of the lack of an adequate theoretical framework. Currently there are two main ways to define halos: the isodensity based "friends-of-friends" (FOF) algorithm, and the spherical overdensity (SO) approach (Fig. 1), which includes all particles within a spherical domain the boundary of which is determined by an overdensity criterion.

Depending on the application, one definition may be favored over the other. For X-ray observations of relaxed clusters, the SO approach appears to be more natural since one fits directly to a spherically averaged profile as is observational practice. However, the mass function of FOF halos has a well-characterized "universal" form often used in theoretical studies. It is therefore highly desirable to find a mapping between these two halo definitions.

In recent work we have succeeded in solving this problem [1], first by establishing a connection between the FOF and SO definitions for a class of idealized dark matter halos described by the Navarro-Frenk-White (NFW) profile [2,3] (Fig. 2). The NFW profile fits results from simulations very well, and is determined by two parameters. We showed how the FOF and SO descriptions of an NFW halo can be mapped

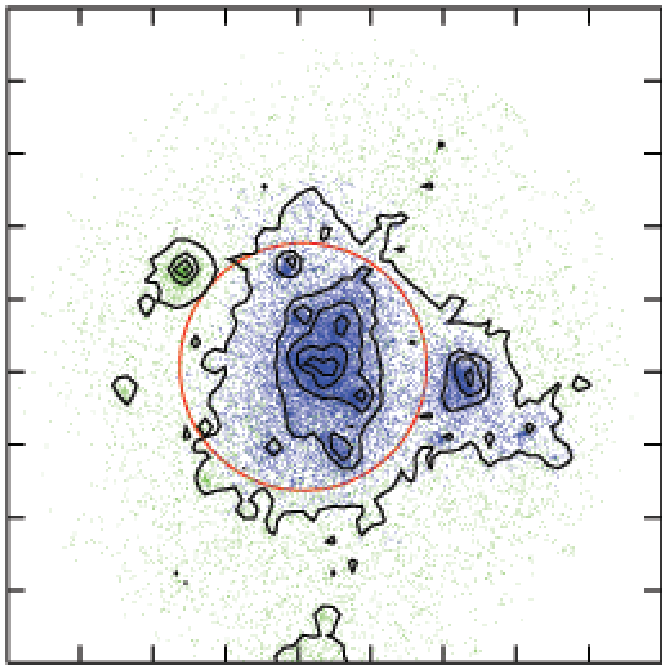

Fig. 1. Different halo definitions for the same particle distribution in a simulation (green points). The black contours are for the projected density field. The blue particles show FOF halo members as determined by a numerical algorithm. The red circle shows the corresponding SO halo centered around the same point as the FOF halo.

into each other as a function of these two parameters with a small scatter dependent on the number of sampling particles. (Previous studies hoping for a simple one-to-one map had failed to properly connect the two mass definitions.)

We next determined that 80-85 percent of the halos found in simulations are relatively isolated and the simple mapping mentioned above is also successful in describing realistic halos. The remaining halos cannot be easily described in simple terms (Fig. 2). A key issue is the occurrence of major substructure (smaller halos associated with a larger parent), leading to what we termed "bridged halos." These halos consist of apparently localized structures linked via density ridges into a common FOF halo.

We have found that the bridged halo fraction rises as a function of mass, and like the FOF mass function itself, also appears to be universal. We also find that in the cluster mass regime the fraction of halos with major satellites as a function of the satellites mass fraction is cosmology dependent. Thus, bridged halos may turn out to be another way to test the dark matter paradigm for structure formation.

The predicted degree of bridging from our simulations is roughly consistent with X-ray observations of clusters, where there is a significant second component within the expected distance in approximately 10-20 % of all cases [4]. As cluster catalogs improve, stronger tests of these predictions may be anticipated, especially by combining multispectral information (microwave, optical, radio, X-ray) from upcoming surveys.

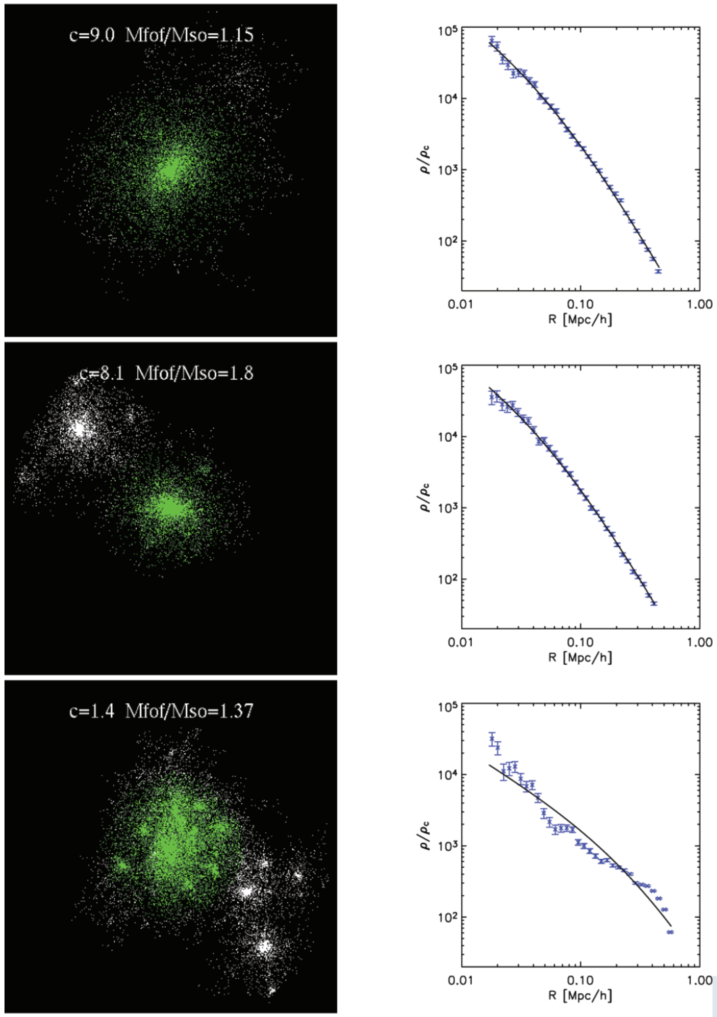

Fig. 2. Top panel: A typical isolated FOF halo (FOF-linked particles shown as white dots) with NFW profile fit to the right. Green dots are particles belonging to the corresponding SO halo. Middle panel: An example of a bridged halo. Bottom panel: A halo with major substucture, for which the NFW profile is not a good fit.

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[1] Z. Lukic et al., *Astrophys. J.* **692,** 217 (2009).
[2] J.F. Navarro, C.S. Frenk, S.D.M. White, *Astrophys. J.* **462,** 563 (1996).
[3] J.F. Navarro, C.S. Frenk, S.D.M. White, *Astrophys. J.* **490,** 493 (1997).
[4] A. Vikhlinin, (private communication).

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